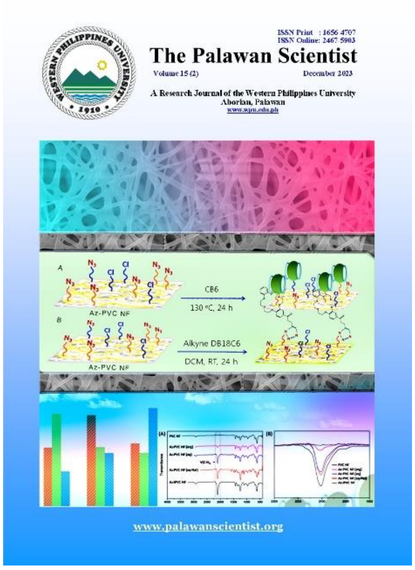
Review Paper



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Current trends in modular wastewater treatment - a patent review

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ABSTRACT

Wastewater is a major source of water pollution, as it contains contaminants from human waste, chemicals, industrial runoff, and other sources that can be harmful to the environment and human health. Therefore, treatment is necessary to reduce its harmful effects. However, wastewater treatment (WWT) is often costly and difficult to implement in many areas. With conventional WWT designs lacking robustness and adaptability, modular designs can be a viable solution for this problem. In this review, a patent survey covering patents from 1996 to 2021 yielded 66 patents regarding modular WWT. The patent search showed increasing patents regarding modular WWT in recent years. Most of the patents were filed by companies in China. The International Patent Classification (IPC) was used to determine the current trends in modular WWT. Current patented designs suggest that there have been attempts to develop modularized electrochemical, separation, and sorption methods. Also, multistep patent designs showed fully integrated modular units from conventional WWT design and offer robustness and adaptability. This patent review showed that modular WWT technologies are capable and ready to be used in different settings.

Keywords: compact wastewater treatment, water pollution, wastewater treatment technologies

INTRODUCTION

Water pollution has become a global concern due to the exponential growth of the world's population and the rapid industrialization and urbanization (Sonune and Ghate 2004). This has led to a scarcity of clean water that makes it necessary to address this issue urgently. Wastewater generated by human activities further contributes to the problem, with an estimated 80% of wastewater worldwide discharged into the environment without adequate treatment (Dutta et al. 2021). This poses a significant challenge, especially for low-income countries where industrial wastewater contains high concentrations of metals, and domestic or municipal wastewater is laden with nutrients. In contrast, high-income countries can treat a larger proportion of their wastewater due to stricter regulations and the presence of wastewater treatment (WWT) facilities (Crini and Lichtfouse 2018; Dutta et al. 2021).

Wastewater treatment processes encompass a range of physical, biological, and chemical techniques that have been extensively studied and applied over the years (Henze et al. 1997; Sonune and Ghate 2004; Anjaneyulu et al. 2005; Barakat 2011; Sharma et al. 2012). Current WWT processes typically involve four main stages: preliminary treatment, primary treatment, secondary treatment, and tertiary treatment. However, these conventional WWT plants suffer from notable drawbacks (Marchesseault et al. 2005; Reilly and Jelderks 2011a; Molinos-Senante et al. 2012; Jin et al. 2014). These challenges include the need for skilled operators, high operational costs, the requirement for overdesigning to accommodate future capacity increases and influent variations, the production of large amounts of waste sludge, and difficulties in adapting to varying influent volumes and contaminant concentrations.

Modular WWT systems offer a promising solution to these challenges by providing a robust, adaptable, and flexible approach to WWT, addressing many of the issues encountered in current designs (Spiller et al. 2015). These systems improve energy efficiency by optimizing the modules used for treating current influent wastewater, thereby reducing energy consumption. Additionally, their compact design minimizes land area requirements, making them suitable for small towns and industries with limited space. Modular treatment systems enable on-site WWT, extending the lifespan of existing facilities and ensuring effective treatment in specific areas. Moreover, modular designs allow for easy expansion by adding additional treatment modules to accommodate increased influent wastewater. Integrating modular WWT systems into current treatment plants can extend their operational life and ensure compliance with new effluent quality regulations.

However, it is crucial for modular systems to deliver comparable performance to conventional WWT plants. The primary objective of WWT is the removal of nutrients, with biodegradation being the preferred mechanism for breaking down these compounds (Dobson and Burgess 2007). The activated sludge process (ASP), a widely employed method, utilizes the aerobic degradation of organic compounds by supplying air to microbial communities in the reactor (Daverey et al. 2019). The ASP is considered a simple and cost-effective approach to WWT. However, current ASP systems are energy-intensive, resulting in high operational costs (Dobson and Burgess 2007; Daverey et al. 2019). To overcome this challenge, alternative secondary treatment technologies, such as membrane bioreactors, moving bed bioreactors, and sequencing batch reactors, have been explored.

This review aims to collect and evaluate patents filed between 1996 and 2021, focusing on the current design trends and technologies used in the development of modular WWT systems. By analyzing these patents, this review serves as a foundation for future advancements in modular WWT systems that will foster sustainability and address the pressing challenges associated with WWT.

PATENT SEARCH METHODOLOGY

Figure 1 shows the patent search methodology used for this study. A keyword search approach was used for the initial patent search using the Espacenet database of the European Patent Office. Generic keywords were used for the initial search which include “modular”, “compact”, “wastewater”, “treatment”, “plant”, “design”, “configuration”, “process”, and “method”. Only those patents relevant to modular WWT were considered, regardless of their International Patent Classification (IPC) classes. The selected patents were downloaded as a search query from the Espacenet database and compiled in an Excel spreadsheet. Two search queries were downloaded from the Espacenet database. The first search query was downloaded from the database on 02 August 2022 and contained 212 patents. The second search query, downloaded from the database on 08 August 2022 contained 54 patents. The patents were then reexamined to exclude searches that did not deal with treating wastewater and lacked modularity. From the previous search queries, only 66 patents were considered. The remaining relevant patents were then reanalyzed via the Google Patents database to find other data about the patent, i.e., patent application date, status, and countries where the patents were approved. The additional information extracted from each patent was done on 04 January 2023.

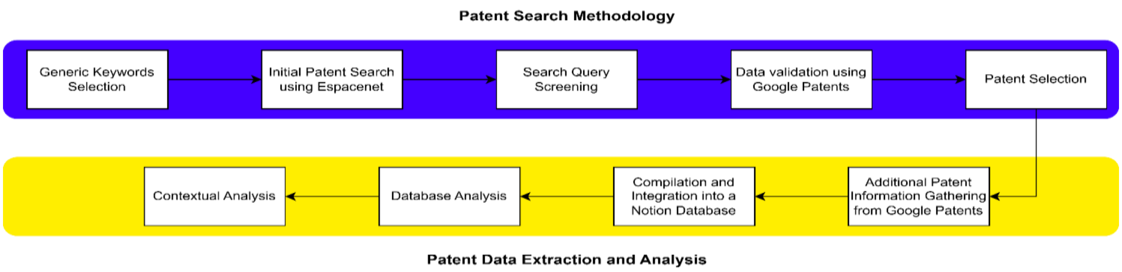

Figure 1. Patent search and data analysis methodology.

PATENT DATA EXTRACTION AND ANALYSIS

A total of 66 patents were found from the Espacenet and Google Patents databases that describe a design or a method of implementing a modular WWT technology. These patents were integrated into a Notion database (https://tinyurl.com/patentswwt). The exported information from each patent includes the patent number, patent name, application date, author/inventor, claims, figures, country of application, patent status, and IPC classes. The considered patents for the database are the applied patents only. However, during data gathering, the subcategories of the filed patents were recorded. The Notion database was used to analyze the patents and filter the patents according to different types of information exported. The filtered patents are used to determine the patent distribution with regard to the date of filing, country, and IPC classes. The claims of each patent were analyzed to give context to its design, validate its IPC classes, and further generalize the current design trends and application of WWT technology.

PATENT SITUATION FOR THE MODULAR WWT PLANT

As shown in Figure 2, the majority of the patents are from China, with 44 patents, followed by the USA with 14, Russia with three, and Australia, Canada, India, Germany, and South Korea with one patent each. Figure 3 shows the distribution of patents based on the year of application and the year of publication. It shows that the number of patent applications increased significantly from 2017 to 2021, with a peak of 10 patent applications in 2020 and 2021. During this period, 66% of the relevant patents for modular WWT were filed. Most of the patents from 1996 to 2016 were filed in the USA. Meanwhile, 38 out of the 45 patents filed from 2017 to 2021 were filed in China.

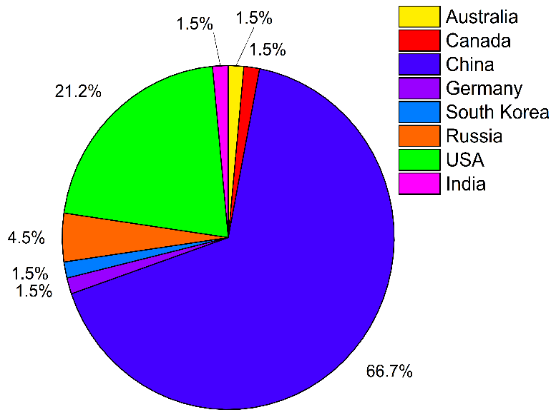

Figure 2. Distribution of patents based on the countries where they were filed.

It was seen that patents filed from 1996 to 2016 experienced slower publication, with an average of 902 days between the date of application and the date of publication. However, this has not been the case recently. Patents from 2017 to 2021 are generally granted faster, with an average of 340 days between the date of application and the date of publication.

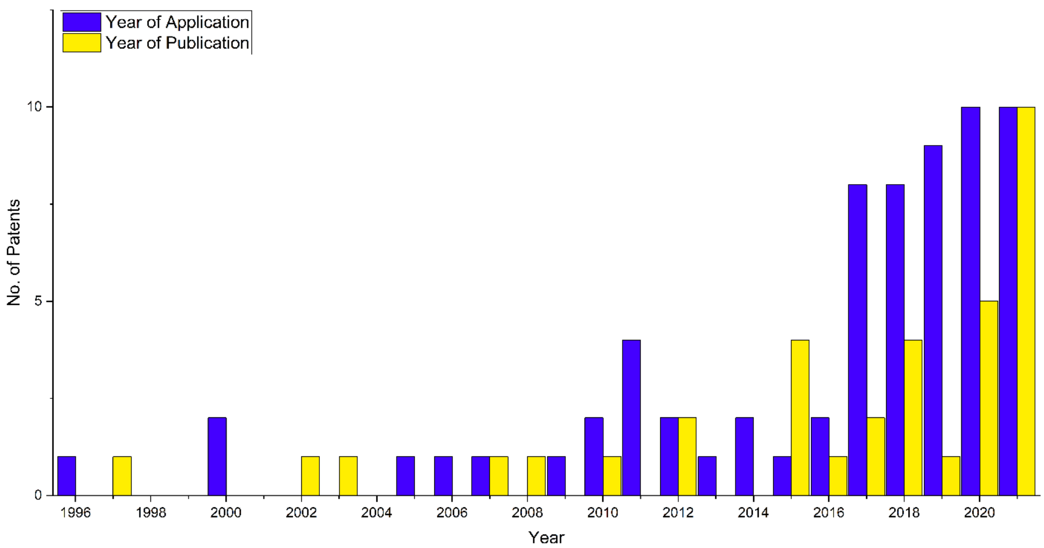

Figure 3. Distribution of patents based on the year of application and year of publication.

Figure 4 shows the distribution of patents based on the number of claims. Thirty-five out of the 66 patents considered in this study have between 6 and 10 claims. This shows that there has been a huge advancement in modular WWT technology. The presence of two patents with more than 41 claims suggests the uniqueness and complexity of their modular system. Furthermore, it is important to consider the implications of claim distribution in the context of intellectual property management and litigation. Patents with a large number of claims are more robust in defending against infringement as they cover a wider scope of potential violations. Conversely, patents with fewer claims could also be more concise and easier to manage.

Figure 5 shows the distribution of patents based on their application status. Currently, there are 34 active patents with modular WWT designs, of which 23 are from China. There is one withdrawn patent (CN108178461A) and two abandoned patents (US2005274669A1 and US20070289922A1). There are 10 expired patents, of which seven are classified as expired due to fee-related issues. As of this writing, there are 19 pending patent applications. Seventeen of them are from China, and two are from the USA.

Figure 6 shows the distribution of patents based on the nature of their current assignee. Most of the relevant patents have companies as their current assignees. Meanwhile, eight patents have universities as their current assignees, and eight patents have no assignee. The presence of multiple companies as patent holders can indicate several key points related to commercialization, technological advancements, and competitiveness within specific industries. Firstly, when numerous companies hold patents, it typically signifies a strong inclination toward commercializing inventions (Mazzoleni and Nelson 1998). Companies, driven by profit motives and the need to stay competitive in the market, tend to direct their innovations towards practical applications that can generate revenue. Also, companies often possess more substantial resources compared to universities, including robust research budgets, specialized facilities, and a skilled workforce (Lockett and Wright 2005). Consequently, a higher prevalence of company-held patents can indicate a faster pace of technological advancement in particular industries (Garavito and Rueda 2021). A greater number of companies holding patents can also foster a competitive ecosystem (Encaoua et al. 2006; Arora et al. 2008). Companies may engage in competition to innovate, which, in turn, promotes continuous enhancements in their products and services. This competitive environment can be advantageous for consumers by offering them a wider array of choices and potentially driving down prices.

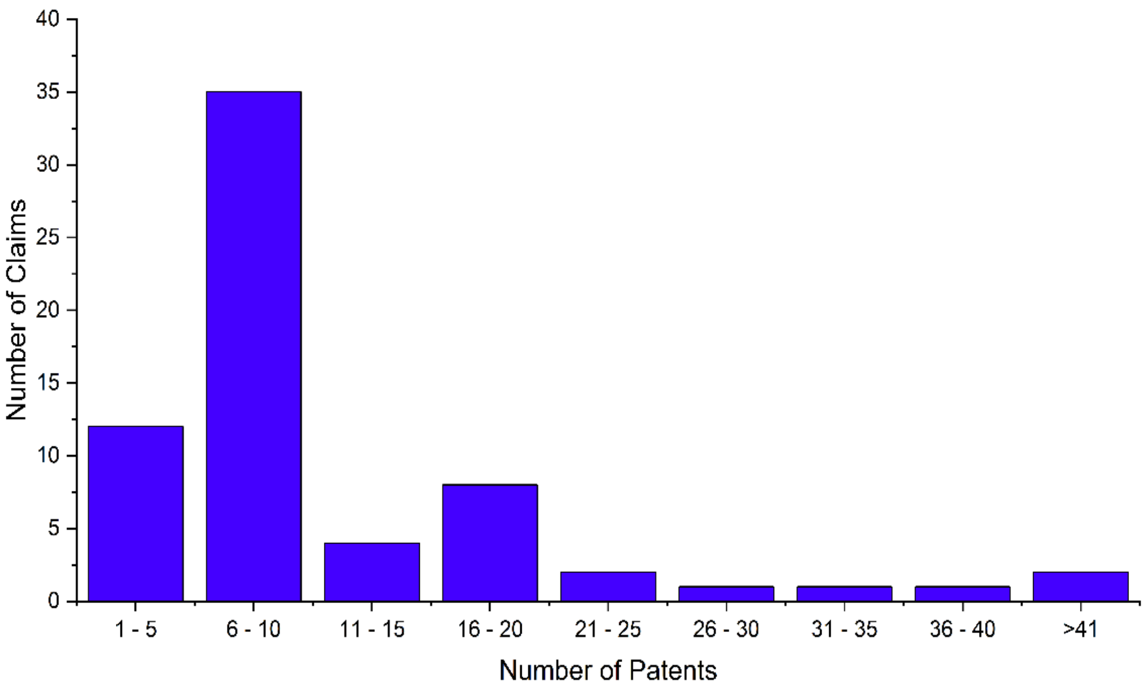

Figure 4. Distribution of patents based on the number of claims.

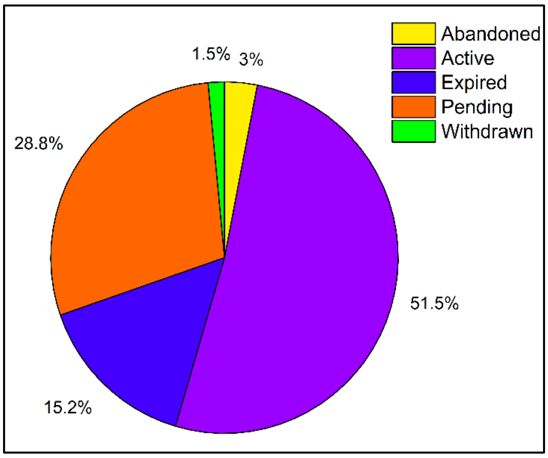

Figure 5. Distribution of patents based on application status.

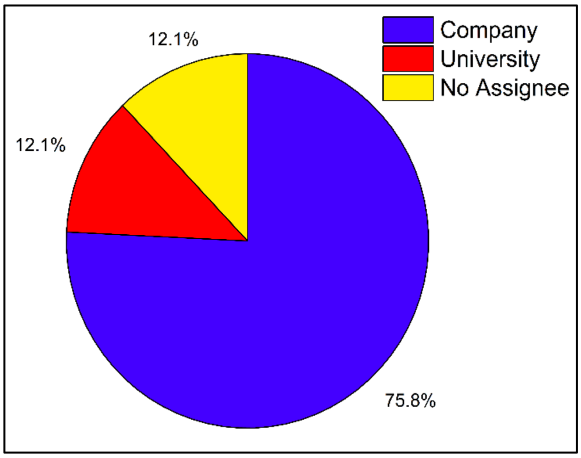

Figure 6. Distribution of patents based on current assignee.

CURRENT DESIGN TRENDS FOR MODULARITY OF WWT PLANT BASED ON THE IPC OF THE PATENTS

For this patent review, the classification considered for the patents is the IPC. This classification features a systematic and uniform means of classifying patents in terms of the area of technology of the patents. It uses a system of letters and numbers to form IPC symbols with class level, subclass level, group level, and subgroup level integrated into a single IPC symbol. Using this classification, it is easier to evaluate the current design trends for modular WWT based on filed patents.

Table 1 summarizes the IPC of the patents considered for this study. In the table, there are seven subclasses under which the 66 relevant patents were classified. This shows that there are numerous attempts at modularization of different technologies for WWT. The subclasses were focused on the separation process (B01D, B65D), treatment of water, wastewater, and sewage (C02F), containers and fixed constructions (E03B, E03F), and process control systems (G05B, G05D). Since the relevant patents pertain to modular WWT systems, groups under the C02F subclass were examined. Figure 7 shows the distribution of patents based on the IPC.

Besides the C02F subclass, the highest number of patents classified under a subclass is five. This subclass is B01D, which covers the separation of solids via physical processes such as filtration and sedimentation. Another subgroup involving separation methods is C02F9/02 where US2005274669A1 is classified. Also, the E03F5/14 subgroup covers the separation of solid or liquid substances from sewage.

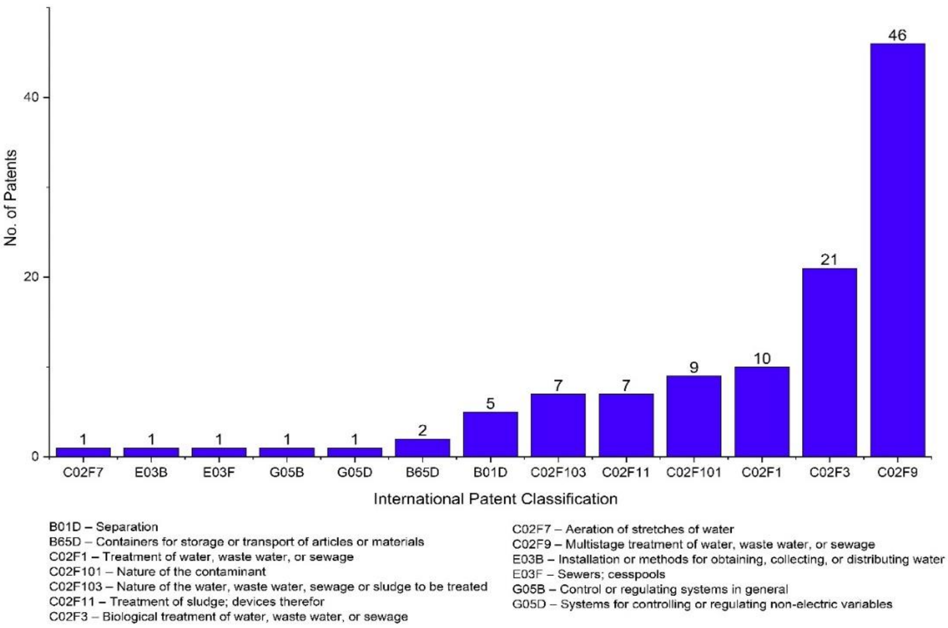

Figure 7. Distribution of patents based on IPC.

This implies that modular primary treatments are already designed and feasible for application. Further implications are the C02F9/08, C02F9/10, and C02F9/12 subgroups, where a total of five patents are classified under these classifications. These subgroups cover multistep WWT involving physical treatment. However, since physical treatment is a rather simpler treatment method than biological and chemical, the small number of patents classified under relevant classifications involving a physical treatment method shows that the modularity of physical treatments has not yet been fully explored.

The B65D and E03B subclasses imply a compact modular WWT design that is flexible to accommodate any wastewater-influent variations. B65D covers the storage and transport of materials. The IPC subgroups under this subclass under which two patents are classified are B65D21/024, B65D21/028, B65D88/010, B65D88/74, B65D90/02, and B65D90/10. The B65D21 group implies a flexible WWT design where modules are made of nestable, stackable, or joinable containers. Only WO2008006175A1 utilized such a design. The E03B subclass further aids the flexibility of WWT design because it considers the arrangement of treatment modules and methods of installation of the modules.

Another approach to having a flexible WWT system is the design disclosed in US2012055883A1. The patent disclosed a system of treatment modules that can go offline or online depending on the treatment needs of the influent wastewater. The patent is classified under the G05B subclass, which covers control systems regulating component variables. Meanwhile, US9079125B2 disclosed a design that has a flow level sensor that adjusts the influent volume dynamically so the treatment system can properly accommodate the influent wastewater. This patent is under the G05D subclass, which covers control systems for non-electrical variables.

From the relevant patents examined, there are already three approaches patented for a flexible and adaptable WWT system. The first is to have a design where modules are stackable and joinable. This signifies a modular system that can increase or decrease its treatment capacity by adding or removing treatment modules. The second approach is to have a control system that can dynamically control which treatment modules should be activated or deactivated to accommodate the varying wastewater influent on the system. The third approach, which is common to non-modular design, is to regulate the volume flow of influent wastewater to prevent overloading the system.

The C02F subclass deals with the treatment of water, wastewater, and sewage. Under this subclass, seven groups were identified by the IPCs of the relevant patents considered for this review. The C02F101 subclass covers the identity of contaminants in water, wastewater, and sewage. The patents showed that the patented modular WWT systems can treat different contaminants, such as heavy metals, inorganic compounds, nitrogen compounds, and organic compounds. This improves the applicability of a modular WWT system to any industry, small business, or municipality.

Common WWTs identified through the C02F1 group are sorption (C02F1/28), UV-light irradiation (C02F1/32), reverse osmosis (C02F1/44), electrochemical methods (C02F1/46), and oxidation with ozone (C02F1/78). Among the 66 patents considered in this review, only 10 are classified under the C02F1 group, as shown in Figure 5. This means that although different treatment methods are explored for modular systems, these designs are not mature and can be further developed. However, this shows that the modularity of WWT methods is feasible, and that further development of modular designs could lead to a higher number of patents being classified under this group. This also shows that different methods can be used as a treatment module for WWT. This means that a modular WWT design has a variety of options to treat a target characteristic of the influent wastewater.

The relevant patents also showed that their modular WWT system is capable of biological treatment. There are 21 patents classified under the C02F3 group and 27 patents under the C02F9/14 subgroup. The biological treatment used in modular designs can be categorized into four – aerobic processes, activated sludge processes, anaerobic digestion, and membrane bioreactors.

There are four patents using the biological treatment of wastewater through aerobic processes, which are classified under C02F3/02 and C02F3/06. The aerobic process disclosed by US9890067 utilized a column design of submerged filters to treat wastewater. Meanwhile, there are eight patents using aerobic and anaerobic processes in their multistep treatment design, as classified under C02F9/14. Designs include modular tanks, ponds, and treatment modules.

Meanwhile, there are 11 patents using the activated sludge process under the C02F3 group. Most of the designs use the conventional activated sludge process. Four patents under C02F9/14 used activated sludge in various integrations in multistep systems. There are also nine patents using anaerobic digestion for biological treatment. The patents generally use anaerobic digestion to have a complete nitrification and denitrification process.

Under the C02F3 group, CN108117150A and CN208055010U utilized membrane bioreactor modules. Furthermore, seven patents under C02F9/14 used membrane technology for their biological treatment in their multistep treatment systems.

The classification of the patents under C02F3 and C02F9/14 shows that even advanced biological treatments can have a modular design, which gives a glimpse of the high treatment efficiency of modular

WWT systems. This shows that biological treatment is now well integrated into modular systems.

Patented modular WWT systems also have sludge treatment modules. There are seven patents that are classified under the C02F11 group. The treatment methods for sludge disclosed by these patents include biological treatment, anaerobic treatment, dewatering and thickening, oxidation, and adding chemical agents. The small number of patents integrating sludge treatment modules into their treatment systems suggests that sludge treatment is not the primary concern of such modular systems. However, the seven patents showed that sludge treatment modules are feasible to integrate into modular systems, making a more complete system.

Among the groups under the C02F subclass, the C02F9 group has the highest number of identified patents. This group covers the multistep treatment of wastewater. The identified subgroups that the patents are classified under involve separation steps (C02F9/02), chemical treatment steps (C02F9/04), electrochemical treatment steps (C02F9/06), physical treatment steps (C02F9/08, C02F9/10, C02F9/12), and biological treatment steps (C02F9/14). As shown in Figure 8, the number of patents being classified under C02F9 is increasing from 2015 to 2021. The high number of patents and the annual increase in the number of patents classified under this group offer two insights. The first is that, due to more complex wastewater influents that need to be treated, a move toward designing a multistep modular treatment system is crucial to preventing untreated wastewater effluent. The second is that, due to the development of different treatment modules through the years, there are now enough designs and methods to integrate different treatment modules into a single modular treatment system. Designing a multistep modular WWT system also offers robustness in terms of treatment efficiency. Multistep treatment offers a higher possibility of removing any unexpected contaminants the influent wastewater may contain.

The current patented modular WWT systems showed the following insights on the treatment system design.

1. Primary treatment methods and secondary biological treatment methods are well integrated into modular systems. This integration ensures that the initial stages of WWT efficiently remove solid materials and pollutants.

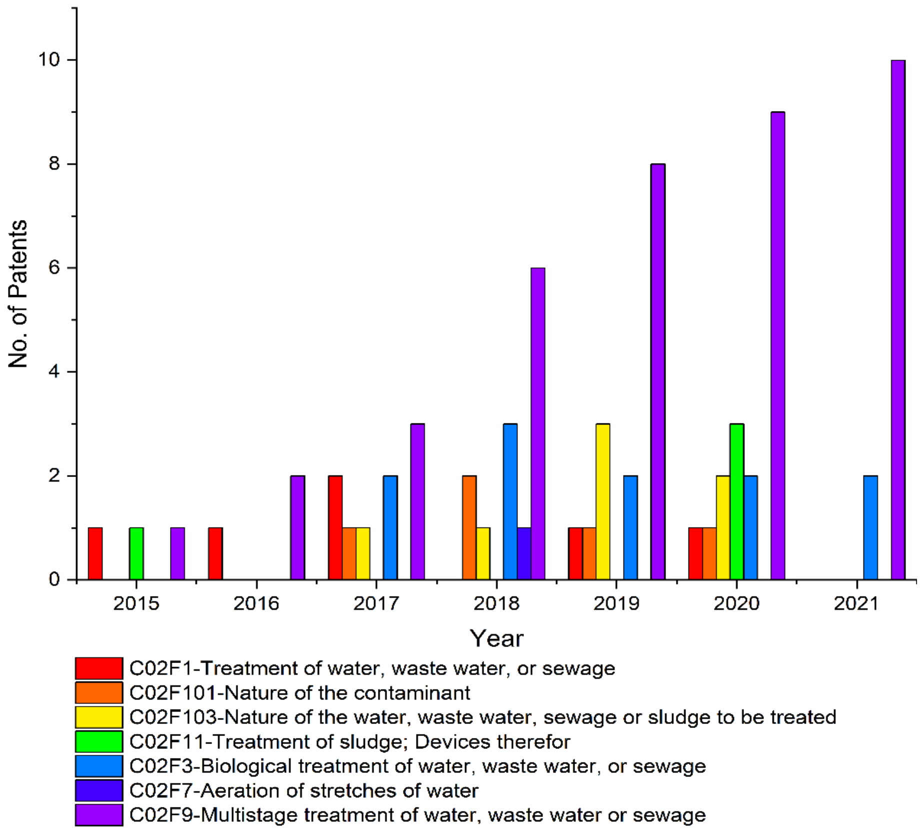

Figure 8. Distribution of patents from 2015-2021 based on the C02F subclass.

Table 1. Current design trends based on International Patent Classification (IPC).

IPC	IPC Title	IPC Description	Sample Patents (Source)	Modular Design Features of the Patents	Source
B01D	Separation of solids	Physical processes such as filtration, sedimentation, crystallization, precipitation, absorption, and adsorption	US9079125B2 (Reilly and Jelderks 2011b) , US9890067 (Monsrreal and Rogelio 2012) KR102069161B1 (Hyun and Choi 2019) CN109381898A (Wang 2017)	Treatment basins removable screens settling baffles filtration via loose material	(WIPO, 2023a)
B65D	Containers for storage and transport	Covers nestable, stackable, or joinable containers	WO2008006175A1 (Wallis 2007) KR102069161B1 (Hyun and Choi 2019)	Rearrangeable tanks with flexible applicability Tank design for wastewater treatment made of reinforced fiber glass	(WIPO, 2023b)
C02F1	Treatment methods for water and wastewater	Covers various methods such as flotation, sorption, irradiation, dialysis, and reverse osmosis	US20160115062 (Krieger 2015) CN102050539A (Zhu et al. 2010) US8318008B1 (Anderson 2009) US9890067 (Monsrreal and Rogelio 2012) CN111302478A (Zhang et al. 2020) CN106966467A (Yang and Li 2017) CN105776442A (Yu et al. 2016)	Flotation system Treatment using activated charcoal Ultraviolet sterilizer Nanofiltration reverse osmosis unit Electrolysis and electrochemical separation Modular electrochemical WWT Ozone disinfection	(WIPO, 2023c)
C02F101	Nature of contaminants in water and wastewater	Covers organic and heavy metal compounds	CN108083579A (Yu et al. 2017), CN113880305A (Luo 2021), CN108911301A (Ren et al. 2018) CN113415959 (Liu et al. 2021), CN113880305A (Luo 2021),	Removal of organic compounds Removal of heavy metals	(WIPO, 2023c)

IPC	IPC Title	IPC Description	Sample Patents (Source)	Modular Design Features of the Patents	Source
			CN215365331U (Hui et al. 2021) CN111573999A (Tong et al. 2010), CN111646648A (Yan et al. 2020), CN110127963A (Xu et al. 2019)	Removal of inorganic, organic, and nitrogen compounds	
C02F103	Nature and origin of wastewater	Covers wastewater from different sources such as mining activities, oilfields, and food industries	CN113415959 (Liu et al. 2021) CN111792764A (Zhang et al. 2020) CN212504336U (Zhang et al. 2020) CN108083579A (Yu et al. 2017)	Treatment of sludge and wastewater Use of trough and subtroughs for connections Treatment of acid mine wastewater Treatment of wastewater from animal husbandry	(WIPO, 2023c)
C02F11	Devices for treating sludge	Covers various treatment methods such as biological, anaerobic, and addition of chemical agents	US6379545B1 (Perslow et al. 2000) US2015014245A1 (Rogelio and Monsrreal 2012) CN111646648A (Yan et al. 2020) RU2741566C1 (Sargin and Vinichenko 2020)	Integrated sludge digester Anaerobic treatment Screw filters for mechanical dewatering Use of chemical agents	(WIPO, 2023c)
C02F3	Biological treatment of water and wastewater	Covers various treatment methods such as aerobic and anaerobic processes using activated sludge	WO2008006175A1 (Wallis 2007) US5688400A (Baxter 1996) US9079125B2 (Reilly and Jelderks 2011b) CN208055010U (Tang and Xu 2018)	Biological filtration Aeration chamber Activated sludge process MBR technology	(WIPO, 2023c)
C02F7	Aeration of stretches of water	Covers aeration of water for WWT	CN108178461A (Hui 2018)	Modular high-efficient film device used to treat and aerate wastewater	(WIPO, 2023c)
C02F9	Multistep treatment of water,	Covers various methods such as chemical, electrochemical,	US20160115062 (Krieger 2015))	Mobile WWT facility with flotation, filtration, chemical, sludge	(WIPO, 2023c)

IPC	IPC Title	IPC Description	Sample Patents (Source)	Modular Design Features of the Patents	Source
	wastewater, and sewage	physical, thermal, and biological processes		treatment modules, and desalination system	
			US2021246058A1 (McFadden 2021)	Two-step treatment of landfill condensate using an aerobic reactor and an anaerobic reactor	
			US2005274669A1 (Marchessault et al., 2005)	Modular transportable WWT system with bioreactor, anoxic tank, membrane filter, and UV disinfection unit	
E03B	Installations used for obtaining, collecting, or distributing water	Covers methods related to water collection	WO2008006175A1 (Wallis 2007)	Water treatment tank design, collection facility	(WIPO, 2023d)
E03F	Fixed constructions of sewers and cesspools	Covers devices for separating liquid or solid substances from sewage	RU2727420C1 (Ermachenko and Bukhantsov 2019)	Modular block unit for primary treatment of wastewater, equipped with device for collecting oils, fats and grease, semi-permissible baffle for retention of floating substances	(WIPO, 2023d)
G05B	Control systems or control elements used in regulating specific variables	Covers control systems for regulating specific variables	US2012055883A1 (Reilly and Jelderks 2011a)	Program control system for monitoring WWT system	(WIPO, 2023e)
G05D	Control systems for regulating non-electrical variables	Covers control systems for regulating non-electrical variables	US9079125B2 (Reilly and Jelderks 2011b)	WWT design equipped with a sensor for detecting wastewater input flow	(WIPO, 2023e)

2. There are already treatment modules that can be integrated into current WWT facilities to upgrade the treatment capabilities and accommodate a higher influent volume. This integration enables the upgrade of treatment capabilities, allowing these facilities to accommodate higher influent volumes without the need for extensive overhauls or expansions.

3. Current trends in modular wastewater systems emphasize multistep treatment processes. This approach results in robust systems capable of producing effluents with wastewater characteristics that meet or even exceed regulatory standards. It ensures a higher level of treatment effectiveness.

4. Patented systems focus on flexibility and adaptability. By adding or regulating treatment

modules, these systems can easily adapt to changing conditions, influent variations, and capacity demands. This adaptability minimizes the need for overdesign, reducing operational costs.

5. Integration of process control systems into current modular WWT design is crucial to achieving an easy-to-operate WWT system. This integration streamlines system operation, making it more user-friendly. Skilled operators become less of a necessity, thus, lowering operational costs.

The current trend observed in this patent review does reflect the existing WWT challenges and problems to some extent. Modular WWT systems, as seen from the IPC of the patents, offer a promising solution to these challenges. The systems offer energy and space efficiency, on-site treatment, scalability, and regulatory compliance. These systems are gaining attention in patents and industry discussions due to several advantages they bring, which align with the ongoing issues in WWT.

CONCLUSION

In recent years, there has been a rise in patent applications for modular WWT systems. This is attributed to the need for many communities and industries to comply with stricter effluent standards. Developed countries such as China and the USA are leading the patent applications for modular WWT systems. Most of the patents have companies as their current assignees. The current patent situation for modular WWT systems shows that there is rapid development in the system approach and design.

The relevant patents are analyzed based on their IPCs. The classifications showed that many different treatment methods have been modularized, such as electrochemical methods, separation methods, and sorption. The modular designs of these systems focus on removing contaminants such as nitrogen compounds, organic compounds, inorganic compounds, and heavy metals. Current designs have fully integrated biological treatments such as aerobic processes, activated sludge processes, and anaerobic digestion. Some of them incorporated sludge treatment via dewatering, chemical agents, biological treatment, and oxidation.

The current trend of modular design offers diverse ways to have an adaptable and flexible design. The current design trend also involves multistep treatment of wastewater, which offers robustness to the system. The integration of control systems as well as the further development of treatment modules will be factors in how the modular WWT system is going to be used in the future.

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ETHICAL CONSIDERATIONS

The conduct of this review did not use/invove any animal or human as subject of the study.

DECLARATION OF COMPETING INTEREST

The authors declare that there are no competing interests for any authors.

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